

Model-Based Fault Diagnosis of Selective Catalytic Reduction Systems for Diesel Engines

Rui Chen and Xinlei Wang
Univ. of Illinois

ABSTRACT

In this paper, a model-based diagnostic system was developed to detect and isolate the dosing fault and the outlet NOx sensor fault for the SCR system. The dosing fault is treated as an actuator additive fault, while the outlet NOx sensor drift and/or offset fault is treated as a sensor additive fault. First, a 0-D SCR model was developed to facilitate the model-based approach. A parity equation residual generator was designed based on the linearized SCR model and the fault transfer function matrix. The diagnostic algorithm is then implemented in the Matlab/Simulink environment for validation. A high fidelity nonlinear 1-D SCR model is used to generate system outputs and to simulate the plant. The simulation results show that the model-based fault diagnosis system succeeds in detecting and isolating the outlet NOx sensor and dosing faults with good sensitivity and robustness

CITATION: Chen, R. and Wang, X., "Model-Based Fault Diagnosis of Selective Catalytic Reduction Systems for Diesel Engines," *SAE Int. J. Passeng. Cars – Electron. Electr. Syst.* 7(2):2014, doi:10.4271/2014-01-0280.

INTRODUCTION

The Nitrogen Oxides (NOx) in the exhaust of a mobile diesel engine are a major threat to the environment, and have been strictly regulated by the Environmental Protection Agency (EPA) of the United States in recent years [1]. To meet the emission regulation, a Selective Catalytic Reduction (SCR) system has been selected by many diesel engine manufacturers. The SCR works by mixing the exhaust gases with ammonia in the form of urea (or Diesel Emissions Fluid, DEF) and passing the mixture through a catalyst. The result is that the majority of NOx in the exhaust will be converted to harmless elemental nitrogen and water vapor. The SCR system is a complex system that contains sensors and actuators that are liable to drift, aging and other faults. The EPA has realized that, and has already enforced On Board Diagnosis (OBD) systems regulations for 2010 and later for heavy-duty diesel engines used for highway applications [2]. The goal is to monitor the SCR conversion efficiency and NOx sensor performance, as well as the actual injection of the SCR reductant.

A common fault in the SCR systems is the dosing fault, which can be caused by various reasons from blockage on the injector nozzle to human tampering of the DEF quality. The dosing fault needs to be detected in order to maintain high NOx conversion efficiency, and therefore meet the emission regulations. There has been some work done in the detection

of the SCR dosing fault using signal based methods [3]. Another common fault in the SCR systems is the NOx sensors, which are installed both at the inlet and outlet of the SCR system to make sure the tailpipe NOx concentration meet the NOx emission requirements. Among them, the outlet NOx sensor reading is more sensitive to small sensor drift and/or offset due to lower NOx concentration at the SCR outlet. The outlet NOx sensor fault also needs to be detected and isolated, because it is critical for determining emission regulation compliance as well as for OBD requirements.

The Fault diagnosis of a diesel SCR system used to have many challenges. One was the lack of mature technology that could enable closed-loop control of an SCR system [4]. Nowadays, both NOx and ammonia sensors have been implemented in feedback control to reduce NOx and ammonia by different manufacturers [5, 6, and 7]. This has given researchers the opportunity to perform more sophisticated diagnosis on SCR systems. In this paper, a model-based diagnosis system was developed to detect and isolate the DEF dosing fault and the outlet sensor fault for the SCR system. First, a lumped parameter SCR model was developed. A parity equation residual generator was designed based on the linearized SCR model and the fault transfer function matrix. The residual generator was then implemented in the Matlab/Simulink environment for validation.

SYSTEM DESCRIPTION

The target diesel engine aftertreatment system consists of a Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), urea decomposition tube, SCR catalyst, and Ammonia Oxidation Catalyst (AOC). The system block diagram is shown in Figure 1.



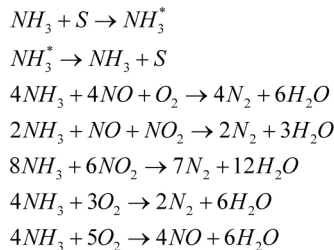
Figure 1. Aftertreatment system block diagram

Two NOx smart sensors are installed after DPF and AOC respectively. An ammonia sensor is installed between the SCR catalyst and the AOC. In order to eliminate undesirable ammonia slip released to the environment, the AOC is installed after the SCR. Also, because the exhaust flow will be fed into the AOC before the outlet NOx sensor, the AOC also eliminates the cross sensitivity of the NOx sensor to ammonia.

SCR SYSTEM MODEL

In this section, a 0-D lumped parameter SCR model was developed. The major assumptions made for this model are listed below:

1. The SCR catalyst is assumed to be a continuously stirred tank reactor.
2. The exhaust flow is a homogeneous, incompressible flow of idea gas.
3. The urea injected to the exhaust flow is completely decomposed and hydrolyzed before entering the SCR catalyst.
4. Only the following reactions were considered: ammonia absorption/desorption, SCR standard/fast/slow reductions, two oxidation reactions of absorbed ammonia.



(1)

5. The seven reaction rates can be expressed using the Eley-Rideal mechanism, in which the reaction rate constants can be defined using the Arrhenius equation

$$\begin{aligned}
 r_{Ads} &= a_1 C_{NH_3} (1 - \theta) & a_1 &= k_{Ads} e^{\frac{-E_{Ads}}{RT}}, \\
 r_{Des} &= a_2 \theta & a_2 &= k_{Des} e^{\frac{-E_{Des}}{RT}}, \\
 r_{st_SCR} &= a_3 C_{NO} \theta & a_3 &= k_{st} e^{\frac{-E_{st}}{RT}}, \\
 r_{fa_SCR} &= a_4 C_{NO} C_{NO_2} \theta & a_4 &= k_{fa} e^{\frac{-E_{fa}}{RT}}, \\
 r_{sl_SCR} &= a_5 C_{NO_2} \theta & a_5 &= k_{sl} e^{\frac{-E_{sl}}{RT}}, \\
 r_{Oxn2} &= a_6 \theta & a_6 &= k_{Oxn2} e^{\frac{-E_{Oxn2}}{RT}}, \\
 r_{Oxno} &= a_7 \theta & a_7 &= k_{Oxno} e^{\frac{-E_{Oxno}}{RT}}
 \end{aligned}$$

(2)

where k_x is the reaction rate constant, and E_x is the activation energy. R is the universal gas constant.

6. The energy released and consumed by the chemical reaction in the catalyst is ignored.
7. The radiation energy released to the atmosphere is also ignored.
8. The exhaust gas temperature in the SCR catalyst is averaged from the measured SCR inlet and outlet temperature:

$$T = \frac{T_{in} + T_{out}}{2}$$

(3)

9. The oxygen concentration is in a range where variations do not affect the reaction rates.
10. The thermal inertia of the catalyst is neglected.

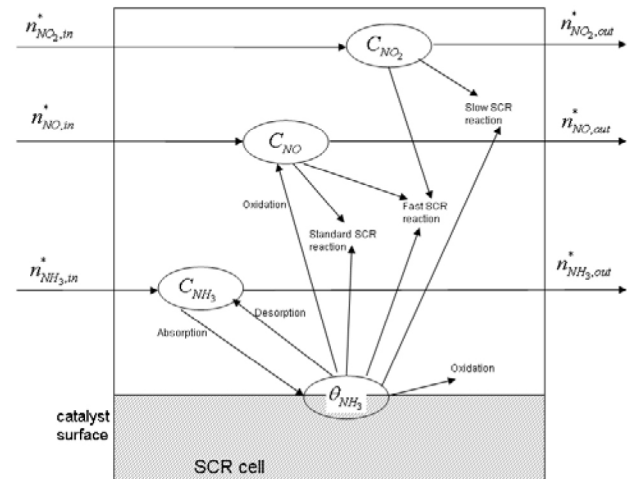


Figure 2. Mass flow and reactions within SCR

According to the mass flow and reactions within the SCR as shown in Figure 2, the dynamics of ammonia coverage ratio θ , gaseous NO, NO₂ and NH₃ concentration, can be determined: